

A Predictive Seesaw Scenario for EDMs

Eung Jin Chun,¹ Antonio Masiero,² Anna Rossi,² and Sudhir K. Vempati^{2,3}

¹*Korea Institute for Advanced Study, Seoul 130-722, Korea*

²*Dipartimento di Fisica “G. Galilei”, Università di Padova and INFN, Sezione di Padova, I-35131 Padova, Italy*

³*Centre de Physique Theorique, Ecole Polytechnique-CPHT, 91128 Palaiseau Cedex, France*

(Dated: February 2, 2008)

The generation of electric dipole moments (EDMs) is addressed in the supersymmetric seesaw scenario realized through the exchange of $SU(2)_W$ triplet states. In particular, we show that the triplet soft-breaking bilinear term can induce finite contributions to lepton and quark EDMs. Moreover, the peculiar flavour structure of the model allows us to predict the EDM ratios d_e/d_μ and d_μ/d_τ only in terms of the neutrino parameters.

Supersymmetric (SUSY) extensions of the Standard Model exhibit plenty of new CP violating phases in addition to the unique CKM phase of the SM. Although new sources of CP violation are welcome to dynamically achieve an adequate matter – antimatter asymmetry, it is known that they constitute a threat for very sensitive CP tests like those of the electric dipole moments (EDMs), at least for SUSY masses which are within the TeV region. In view of such constraints as well as of those coming from flavour changing neutral current processes, one can safely assume that all the terms which softly break SUSY are real and flavor universal at the scale where supersymmetry breaking is communicated to the visible sector. In spite of this, their renormalization group (RG) running down to the electroweak scale feels the presence of the Yukawa couplings in the superpotential which can induce flavor and CP violation in the soft breaking sector at low energy. Hence, in this class of minimal supersymmetric extensions of the Standard Model (MSSM), the CP and flavour violating radiative effects are effectively encoded in the CKM mixing matrix, and therefore can be within the experimental constraints.

This picture can drastically change if there are additional sources of flavour violation in the superpotential. This is what happens in the case of the seesaw mechanism which entails new lepton flavour violating (LFV) and CP violating (CPV) Yukawa couplings to generate neutrino masses [1]. Regarding the standard (so-called type-I) seesaw mechanism [2], the phenomenological implications of the RG-induced LFV and CPV effects for rare decays such as $\mu \rightarrow e + \gamma$ and leptonic EDMs have been studied in detail in several works [3, 4].

In addition to the logarithmically divergent RG corrections, there are additional finite contributions to the soft SUSY terms in the seesaw mechanism. In type-I seesaw, these contributions are induced by the bilinear soft-term $\mathbf{B}_N \mathbf{M}_N \tilde{N} \tilde{N}$, associated with the Majorana mass matrix \mathbf{M}_N for the heavy singlet states N . The fact that they can be significant and even comparable to the usual RG-induced contributions has been recently shown in Ref. [5]. If the only source of CPV resides in the soft ma-

trix \mathbf{B}_N , then the most stringent constraint arises from the lepton EDMs. We recall that the flavour structure of the infinite radiative contributions to the soft-breaking terms is determined by the Dirac-like Yukawa couplings \mathbf{Y}_N of the $SU(2)_W$ lepton doublets with the heavy states N . In general the Yukawa couplings \mathbf{Y}_N are arbitrary complex parameters and, moreover, not directly related to the low-energy neutrino mass matrix \mathbf{m}_ν . Regarding the finite radiative corrections, they exhibit in general a different flavour structure from the infinite one, as the soft parameter \mathbf{B}_N is a symmetric matrix in the generation space, not related to the neutrino mass matrix \mathbf{m}_ν . Hence both the above radiative corrections cannot be predicted in terms of known low-energy observables [6].

In this Letter we propose a predictive alternative by considering the triplet seesaw mechanism where neutrino masses are generated through the exchange of one pair of $SU(2)_W$ triplet states T, \bar{T} with nonzero hypercharge (this realization is similar to what was initially suggested in Refs. [7, 8] and, for concreteness, we consider here the supersymmetrized version in Ref. [9]) Indeed, in this case the flavour structure of the (finite and infinite) radiative corrections can be rewritten in terms of the low-energy neutrino masses and mixing angles up to an overall mass scale. Furthermore, assuming no new SUSY CP violating phases, leptonic EDMs can be shown to be proportional to the smallest neutrino mixing angle, θ_{13} . Here we propose a supersymmetry breaking scenario where the soft-term $B_T M_T T \bar{T}$ is the *only* new source of CP violation. In such a situation large leptonic and hadronic EDMs can be generated, for a reasonable SUSY mass spectrum, and interestingly enough, the ratios of the resultant leptonic EDMs are completely determined by the low-energy neutrino data and are independent of the soft spectrum. Such a predictive power is directly linked to the above assumption on the uniqueness of the CPV phase. In view of our ignorance on the SUSY breaking mechanism, we are led to make assumptions in order to reduce the number of CP phases in a generic MSSM frame. This is what we do here with the advantage that our assumption leads

to testable predictions as we will show.

In the type-I seesaw mechanism the superpotential reads:

$$W = W_0 + W_N \quad (1)$$

with

$$\begin{aligned} W_0 &= \mathbf{Y}_e H_1 e^c L + \mathbf{Y}_d H_1 d^c Q + \mathbf{Y}_u H_2 u^c Q + \mu H_1 H_2 \\ W_N &= \mathbf{Y}_N H_2 N L + \frac{1}{2} \mathbf{M}_N N N, \end{aligned} \quad (2)$$

where we have used the standard notation and family indices are understood. Assuming flavor universality and CP conservation of the SUSY sector, finite [5] and infinite [4] LFV and CPV radiative corrections are induced by the new flavour structures (\mathbf{Y}_N and \mathbf{M}_N). Such contributions are proportional to the quantity $\mathbf{Y}_N^\dagger \mathbf{Y}_N$. In spite of this dependence on the “leptonic” quantity \mathbf{Y}_N , it is worthwhile emphasizing that these contributions affect also the hadronic EDMs, a point which was missed in the literature. In particular, this applies to the finite contributions to the trilinear \mathbf{A}_u term which is corrected as:

$$\delta \mathbf{A}_u = -\frac{1}{16\pi^2} \mathbf{Y}_u \text{tr}(\mathbf{Y}_N^\dagger \mathbf{B}_N \mathbf{Y}_N), \quad (3)$$

leading to quark EDMs, and thus to a nonzero neutron EDM. The scheme yields the following ratios of EDMs:

$$\frac{d_\mu}{d_e} \approx \frac{m_\mu}{m_e} \frac{(\mathbf{Y}_N^\dagger \mathbf{B}_N \mathbf{Y}_N)_{22}}{(\mathbf{Y}_N^\dagger \mathbf{B}_N \mathbf{Y}_N)_{11}}, \quad \frac{d_u}{d_e} \approx C \frac{m_u}{m_e} \frac{\text{tr}(\mathbf{Y}_N^\dagger \mathbf{B}_N \mathbf{Y}_N)}{(\mathbf{Y}_N^\dagger \mathbf{B}_N \mathbf{Y}_N)_{11}}, \quad (4)$$

where C is a factor depending on the soft mass parameters. The above ratios (4) are strongly model-dependent given their dependence on the combination $\mathbf{Y}_N^\dagger \mathbf{B}_N \mathbf{Y}_N$ ¹.

A more predictive picture for LFV and CPV can emerge in the triplet seesaw case [8, 9]. Here the MSSM superpotential W_0 is augmented by:

$$W_T = \frac{1}{\sqrt{2}} (\mathbf{Y}_T L T L + \lambda_1 H_1 T H_1 + \lambda_2 H_2 \bar{T} H_2) + M_T T \bar{T} \quad (5)$$

where the supermultiplets $T = (T^0, T^+, T^{++})$, $\bar{T} = (\bar{T}^0, \bar{T}^-, \bar{T}^{--})$ are in a vector-like $SU(2)_W \times U(1)_Y$ representation, $T \sim (3, 1)$ and $\bar{T} \sim (3, -1)$. \mathbf{Y}_T , a complex symmetric matrix, is characterized by 6 independent moduli and 3 physical phases, while the parameters λ_2 and M_T can be taken to be real, and λ_1 is in general complex. After integrating out the triplet states at the scale M_T , the resulting neutrino mass matrix becomes

$$\mathbf{m}_\nu = \mathbf{U}^* \mathbf{m}_\nu^D \mathbf{U}^\dagger = \frac{v_2^2 \lambda_2}{M_T} \mathbf{Y}_T, \quad (6)$$

¹ The RG evolution spoils the possible (high-scale) flavour blind structure of the matrix \mathbf{B}_N through the contributions of the ‘flavoured’ trilinear couplings $\mathbf{A}_N H_2 \bar{N} \bar{L}$.

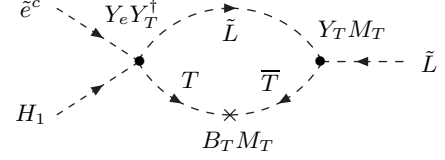


FIG. 1: Example of one-loop finite contribution to the trilinear coupling $\mathbf{A}_e H_1 \tilde{e}^c \tilde{L}$, induced by the bilinear term $B_T M_T T \bar{T}$.

where \mathbf{m}_ν^D is the diagonal neutrino mass matrix and \mathbf{U} is the PMNS leptonic mixing matrix, which is parametrized as $\mathbf{U} = \mathbf{V}[\theta_i, \delta] \mathbf{P}[\phi_a]$ ($\theta_i, i = 1, 2, 3$ are the mixing angles, δ is the Dirac phase, while $\phi_a, a = 1, 2$ are the Majorana phases). Eq. (6) shows that the nine independent parameters contained in \mathbf{Y}_T are in *one-to-one* correspondence with the low-energy neutrino parameters described by the quantities \mathbf{U} and \mathbf{m}_ν^D . As a consequence unambiguous predictions on the low-energy LFV phenomena can be derived in the triplet seesaw model [9, 10]. We now turn to the EDM predictions in this model. First of all, out of the three phases present in the neutrino sector, only the Dirac phase δ may entail CP-violating effects in the LFV entries (this is due to the symmetric nature of \mathbf{Y}_T). However, the contributions to physical observables such as the EDMs turn out to be quite suppressed in general. Indeed, due to the hermiticity of $\mathbf{Y}_T^\dagger \mathbf{Y}_T$, the phase of the electron EDM amplitude is always proportional to the small neutrino mixing angle θ_{13} and to a high power of the Yukawa couplings. Only in very special circumstances with θ_{13} close to the present experimental limit and very large $\tan \beta$, these contributions could become sizeable.

On the other hand, a single CP phase residing in the soft term $B_T M_T T \bar{T}$ can play a significant role in generating non-zero EDMs, once we assume vanishing CP phases in μ and tree-level A -terms. In such a case, the trilinear couplings $\mathbf{A}_e, \mathbf{A}_d, \mathbf{A}_u$ receive finite ‘complex’ radiative corrections at the decoupling of the heavy states T, \bar{T} , exhibiting the common phase from the soft-term B_T ². In Fig. 1 we show the diagrammatic contribution to \mathbf{A}_e proportional to $\mathbf{Y}_T^\dagger \mathbf{Y}_T$. Similar diagrams generate other contributions proportional to $|\lambda_i|^2$, relevant for $\mathbf{A}_e, \mathbf{A}_d$ and \mathbf{A}_u . Thus we obtain:

$$\delta \mathbf{A}_e = -\frac{3}{16\pi^2} \mathbf{Y}_e \left(\mathbf{Y}_T^\dagger \mathbf{Y}_T + |\lambda_1|^2 \right) B_T,$$

² In fact, the B_T -term also induces finite complex corrections to the Higgs bilinear term $B \mu H_1 H_2$ proportional to $(|\lambda_1|^2 + |\lambda_2|^2)$. However, the effect of the related CPV phase on the leptonic EDMs can be suppressed if *e.g.* the combination $(|\lambda_1|^2 + |\lambda_2|^2)$ is much smaller than $\mathbf{Y}_T^\dagger \mathbf{Y}_T$. In this case the dominant contributions to the leptonic EDMs are those driven by the trilinear couplings as discussed here.

$$\begin{aligned}\delta\mathbf{A}_d &= -\frac{3}{16\pi^2}\mathbf{Y}_d|\lambda_1|^2 B_T, \\ \delta\mathbf{A}_u &= -\frac{3}{16\pi^2}\mathbf{Y}_u|\lambda_2|^2 B_T.\end{aligned}\quad (7)$$

The lepton (quark) EDMs arise from one-loop diagrams that involve the exchange of sleptons (squark) of both chiralities and Bino (gluino) (at leading order in the electroweak breaking effects). The parametric dependence of the EDMs at the leading order in the trilinear couplings goes as follows

$$\begin{aligned}\frac{(d_e)_i}{e} &\approx \frac{-\alpha}{4\pi c_W^2} m_{e_i} \frac{M_1 \text{Im}(\delta\hat{\mathbf{A}}_e)_{ii}}{m_L^4} F(x_1), \\ \frac{(d_d)_i}{e} &\approx \frac{-2\alpha_s}{9\pi} m_{d_i} \frac{M_3 \text{Im}(\delta\hat{\mathbf{A}}_d)_{ii}}{m_Q^4} F(x_3), \\ \frac{(d_u)_i}{e} &\approx \frac{4\alpha_s}{9\pi} m_{u_i} \frac{M_3 \text{Im}(\delta\hat{\mathbf{A}}_u)_{ii}}{m_Q^4} F(x_3),\end{aligned}\quad (8)$$

where M_1 and M_3 are the Bino and gluino masses, respectively, the trilinear couplings have been parametrized as $\delta\mathbf{A}_f = \mathbf{Y}_f \delta\hat{\mathbf{A}}_f$ ($f = e, u, d$), and $F(x)$ ($x_1 = M_1^2/m_L^2, x_3 = M_3^2/m_Q^2$) is a loop function whose expression can be found *e.g.* in Ref. [11]. Finally, by using eqs. (7,8), we arrive at the main result of our work, namely the ratio of the leptonic EDMs can be predicted only in terms of the neutrino parameters:

$$\frac{d_\mu}{d_e} \approx \frac{m_\mu}{m_e} \frac{[\mathbf{V}(\mathbf{m}^D)_\nu^2 \mathbf{V}^\dagger]_{22}}{[\mathbf{V}(\mathbf{m}^D)_\nu^2 \mathbf{V}^\dagger]_{11}}, \quad \frac{d_\tau}{d_\mu} \approx \frac{m_\tau}{m_\mu} \frac{[\mathbf{V}(\mathbf{m}^D)_\nu^2 \mathbf{V}^\dagger]_{33}}{[\mathbf{V}(\mathbf{m}^D)_\nu^2 \mathbf{V}^\dagger]_{22}}, \quad (9)$$

where $d_e \equiv (d_e)_1, d_\mu \equiv (d_e)_2$ *etc.*, and for simplicity we have assumed $|\lambda_1|^2 \ll (\mathbf{Y}_T^\dagger \mathbf{Y}_T)_{ii}$. Notice that the presence of extra CPV phases would alter the simple form of the above ratios (9) and in general the result would be more model dependent. Regarding some numerical insight, we can consider three different neutrino mass patterns: the hierarchical pattern of $m_1 < m_2 \ll m_3$ (HI); the inverted hierarchy of $m_2 > m_1 \gg m_3$ (IH); and the almost degenerate pattern of $m_1 \approx m_2 \approx m_3$ (DG). For each case, the relative size of the entries in eq. (9) is given as follows:

$$\begin{aligned}[\mathbf{V}(\mathbf{m}^D)_\nu^2 \mathbf{V}^\dagger]_{11} : [\mathbf{V}(\mathbf{m}^D)_\nu^2 \mathbf{V}^\dagger]_{22} : [\mathbf{V}(\mathbf{m}^D)_\nu^2 \mathbf{V}^\dagger]_{33} \\ = \begin{cases} c_{13}^2 s_{12}^2 + \rho s_{13}^2 : \rho c_{13}^2 s_{23}^2 : \rho c_{13}^2 c_{23}^2 & \text{(HI)} \\ c_{13}^2 : c_{23}^2 : s_{23}^2 & \text{(IH)} \\ 1 : 1 : 1 & \text{(DG)} \end{cases} \quad (10)\end{aligned}$$

where $\rho = \frac{\Delta m_{31}^2}{\Delta m_{21}^2} \sim 25$ and $s_{ij}(c_{ij}) = \sin\theta_{ij}(\cos\theta_{ij})$. Therefore, according to eq. (9) and using the present best fit neutrino parameters [12] with $s_{13} \ll 0.1$, we obtain the following leptonic EDM ratios:

$$\frac{d_\mu}{d_e} \approx \frac{m_\mu}{m_e} \frac{\rho s_{23}^2}{s_{12}^2} \sim 10^4, \quad \frac{d_\tau}{d_\mu} \approx \frac{m_\tau}{m_\mu} \frac{s_{23}^2}{c_{23}^2} \sim 17, \quad \text{(HI)}$$

EDM	Present limits	Future limits
d_e	7×10^{-28} [13]	10^{-32} [14]
d_μ	3.7×10^{-19} [13]	$10^{-24} - 5 \times 10^{-26}$ [15]
$\text{Re}(d_\tau)$	4.5×10^{-17} [13]	$10^{-17} - 10^{-18}$
d_n	6×10^{-26} [13]	??

TABLE I: Present bounds and future sensitivity (in e-cm units) on lepton and neutron EDMs.

$$\frac{d_\mu}{d_e} \approx \frac{m_\mu}{m_e} c_{23}^2 \sim 10^2, \quad \frac{d_\tau}{d_\mu} \approx \frac{m_\tau}{m_\mu} \frac{s_{23}^2}{c_{23}^2} \sim 17, \quad \text{(IH)}$$

$$\frac{d_\mu}{d_e} \approx \frac{m_\mu}{m_e} \sim 2 \times 10^2, \quad \frac{d_\tau}{d_\mu} \approx \frac{m_\tau}{m_\mu} \sim 17, \quad \text{(DG)}. \quad (11)$$

We are now tempted to give an order-of-magnitude estimate of d_e to show that sizeable values can be attained:

$$\frac{d_e}{e} \sim 10^{-29} \left(\frac{M_T}{10^{11} \text{ GeV}} \cdot \frac{10^{-4}}{\lambda_2} \right)^2 \left(\frac{200 \text{ GeV}}{\tilde{m}} \right)^2 \text{ cm} \quad (12)$$

where we have taken a common SUSY mass scale, $M_1 = m_L = \text{Im}(B_T) = \tilde{m}$ and the pattern HI. This shows that the electron and muon EDMs could be within the future experiment reach (see Table 1). We also notice from eq. (7) that lepton and quark EDMs are definitely correlated in this scenario. However, such a correlation is also sensitive to the ratio M_T/λ_2 and to other mass parameters, such as the gaugino, squark and slepton masses, and so can only be established in a specific SUSY breaking framework.

Another interesting prediction regards the relative size of LFV among different flavours [9]. For instance, the ratio of the LFV entries of the left-handed slepton mass matrix is:

$$\frac{(\mathbf{m}_L^2)_{\tau\mu}}{(\mathbf{m}_L^2)_{\mu e}} \approx \frac{(\mathbf{Y}_T^\dagger \mathbf{Y}_T)_{23}}{(\mathbf{Y}_T^\dagger \mathbf{Y}_T)_{12}} \approx \rho \frac{\sin 2\theta_{23}}{\sin 2\theta_{12} \cos \theta_{23}} \sim 40 \quad (13)$$

which holds for $s_{13} \ll \rho^{-1} c_{12} s_{12} \sim 0.02$. This implies that also the branching ratios $B(\ell_i \rightarrow \ell_j \gamma)$ can be related in terms of only the low-energy neutrino parameters and we find

$$B(\mu \rightarrow e \gamma) : B(\tau \rightarrow e \gamma) : B(\tau \rightarrow \mu \gamma) \sim 1 : 10^{-1} : 300. \quad (14)$$

This result does not depend on the detail of the model, such as either M_T or the SUSY spectrum [9]. On the contrary, the individual branching ratios in (14) also depend on quantities such as $\mu, \tan\beta$ and soft SUSY parameters, which are not of direct concern in the present discussion of the EDMs.

The presence of triplet states with mass smaller than the grand unification scale M_G precludes the gauge-coupling unification. This can be recovered, for instance, by completing a GUT representation where T, \bar{T} fit. In

such a case care should be taken in evaluating the radiative effects as the additional components of the full GUT multiplet where triplets reside would also contribute to LFV as well as CPV processes. For an explicit example, see, for instance, Ref.[9].

We have focused on the generation of lepton and quark EDMs in the triplet-seesaw scenario by assuming that only the soft parameter B_T has a nonzero phase. Though we believe that realistic supersymmetry-breaking mechanisms can realize such a scenario, we have not addressed this interesting issue in this Letter. We find that the inter-family ratios d_μ/d_e and d_τ/d_μ are determined only by the low-energy neutrino parameters and so are independent of the details of the model (such as the SUSY spectrum or the ratio M_T/λ_2). The leptonic EDMs are also correlated with the quark EDMs. This correlation is somewhat more model dependent, since it may depend *e.g.* on the SUSY breaking scenario and therefore it would deserve a more detailed analysis which is beyond the scope of this work. This model dependence is also present in the correlation among the fermion EDMs and LFV processes, such as $\mu \rightarrow e\gamma, \tau \rightarrow \mu\gamma$. Nevertheless, the EDM relations (9) and the radiative-decay BR ratios (14) are unique signature to test the triplet-seesaw scenario in the upcoming experiments. Finally, we recall another role played by the term B_T in the context of ‘soft’ leptogenesis [16]. Namely, leptogenesis can be realized with only a single pair of triplets T, \bar{T} , via the L violating decays of the latter, thanks to the resonant enhancement induced by the mass splitting $B_T M_T$ between the triplet mass eigenstates. Moreover, in this picture CP asymmetries arise from nonzero relative phases among the superpotential W_T and related soft trilinear couplings³.

Acknowledgements: E. J. C was supported by the Grant, KRF-2002-070-C00022. The work of A. R. has been partially supported by the EU HPRN-CT-2000-00148 (Across the Energy Frontier) and HPRN-CT-2000-00149 (Collider Physics) contracts. S. K. V. acknowledges support from the Italian MIUR under the program ‘PRIN: Astroparticle Physics 2002 and Indo-French Centre for Promotion of Advanced Research (CEFIPRA) project No: 2904-2 ‘Brane World Phenomenology. He is also partially supported by INTAS grant, 03-51-6346, CNRS PICS # 2530, RTN contracts MRTN-CT-2004-005104 and MRTN-CT-2004-503369 and by a European Union Excellence Grant, MEXT-CT-2003-509661.

³ The complex B_T -term also induces finite corrections to the other soft-trilinear terms related to the couplings $\mathbf{Y}_T, \lambda_1, \lambda_2$ in W_T of eq. (5). In this way, an unremovable CP phase emerges among those related couplings.

- [1] F. Borzumati and A. Masiero, Phys. Rev. Lett. **57**, 961 (1986).
- [2] P. Minkowski, Phys. Lett. B **67** 421 (1977); M. Gell-Mann, P. Ramond and R. Slansky, in *Supergravity*, eds. P. Van Nieuwenhuizen and D. Freedman (North-Holland, Amsterdam, 1979), p. 315; T. Yanagida, in *Proceedings of the Workshop on the Unified Theory and the Baryon Number in the Universe*, eds. O. Sawada and A. Sugamoto (KEK, Tsukuba, 1979), p. 95; S.L. Glashow, in *Quarks and Leptons*, eds. M. Lévy et al., (Plenum, 1980, New-York), p. 707; R.N. Mohapatra and G. Senjanović, Phys. Rev. Lett. **44**, 912 (1980).
- [3] J. Hisano, T. Moroi, K. Tobe and M. Yamaguchi, Phys. Rev. D **53**, 2442 (1996); J. Hisano, T. Moroi, K. Tobe and M. Yamaguchi, Phys. Lett. B **391**, 341 (1997) [Erratum-ibid. B **397** (1997), 357 (1997)]; J. Hisano, D. Nomura and T. Yanagida, Phys. Lett. B **437**, 351 (1998); J. Hisano and D. Nomura, Phys. Rev. D **59**, 116005 (1999); J. Hisano and K. Tobe, Phys. Lett. B **510**, 197 (2001); J. A. Casas and A. Ibarra, Nucl. Phys. B **618**, 171 (2001); A. Masiero, S. K. Vempati and O. Vives, Nucl. Phys. B **649**, 189 (2003). For a more complete set, please see, A. Masiero, O. Vives and S. Vempati, New J. Phys. **6**, 202 (2004).
- [4] J. R. Ellis, J. Hisano, S. Lola and M. Raidal, Nucl. Phys. B **621**, 208 (2002); J. R. Ellis, J. Hisano, M. Raidal and Y. Shimizu, Phys. Lett. B **528**, 86 (2002). I. Masina, Nucl. Phys. B **671**, 432 (2003); Y. Farzan and M. E. Peskin, Phys. Rev. D **70**, 095001 (2004).
- [5] Y. Farzan, Phys. Rev. D **69**, 073009 (2004); hep-ph/0411358.
- [6] S. Davidson and A. Ibarra, Phys. Lett. B **535**, 25 (2002).
- [7] R. Barbieri, D.V. Nanopolous, G. Morchio and F. Strocchi, Phys. Lett. B **90**, 91 (1980); R. N. Mohapatra and R. E. Marshak, Proceedings of the *Orbis Scientiae, January, 1980*, p. 277 (Plenum Press, ed. B. Korsonoglu et al); T. P. Cheng and L. F. Li, Phys. Rev. D **22**, 2860 (1980); J. Schechter and J. W. F. Valle, Phys. Rev. D **22**, 2227 (1980).
- [8] M. Magg and Ch. Wetterich, Phys. Lett. B **94**, 61 (1980); Ch. Wetterich, Nucl. Phys. **187**, 343 (1981); R. N. Mohapatra and G. Senjanovic, Phys. Rev. D **23**, 165 (1981); R. N. Mohapatra and P. B. Pal, *Massive Neutrinos in Physics and Astrophysics, First Edition, 1991*, p. 127 and 128; Eq. 7.19; E. Ma and U. Sarkar, Phys. Rev. Lett. **80**, 5716 (1998); E. Ma, M. Raidal and U. Sarkar, Phys. Rev. Lett. **85**, 3769 (2000).
- [9] A. Rossi, Phys. Rev. D **66**, 075003 (2002).
- [10] In this respect for the non-supersymmetric triplet seesaw version, see: E. J. Chun, K.Y. Lee and S.C. Park, Phys. Lett. B **566**, 142 (2003).
- [11] F. Gabbiani, E. Gabrielli, A. Masiero and L. Silvestrini, Nucl. Phys. B **477**, 321 (1996).
- [12] M. H. Ahn *et al.* [K2K Collab.], Phys. Rev. Lett. **90**, 041801 (2003); K. Eguchi *et al.* [KamLAND Collab.], Phys. Rev. Lett. **90**, 021802 (2003); S. N. Ahmed *et al.* [SNO Collab.], arXiv:nucl-ex/0309004; M. Ishitsuka [Super-K Collab.], arXiv:hep-ex/0406076.
- [13] S. Eidelman *et al.* [Particle Data Group Collaboration], Phys. Lett. B **592**, 1 (2004).
- [14] S.K. Lamoreaux, arXiv:nucl-ex/0109014.

- [15] Y.K. Semertzidis, *et al*, arXiv:hep-ph/0012087; J. Aysto, *et al*, arXiv:hep-ph/0109217.
- [16] G. D'Ambrosio, T. Hambye, A. Hektor, M. Raidal and A. Rossi, Phys. Lett. B **604**, 199 (2004).